ECE 322L
Electronics 2

04/02/20 - Lecture 19

Gain-bandwidth product

Augmented π model for a MOSFET

Frequency response of MOSFETs and BJTs

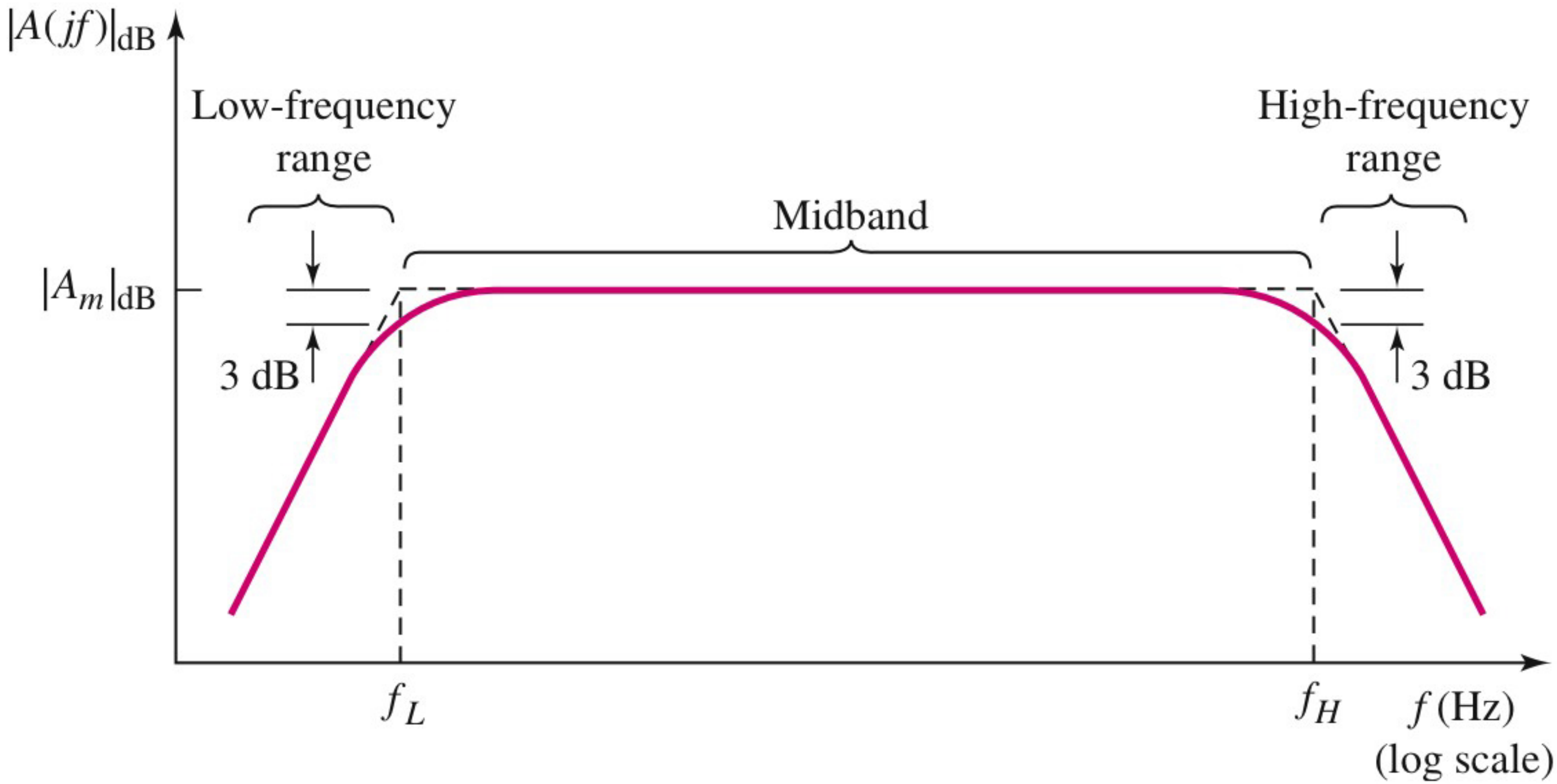
Updates and overview

- Midterm 2 next week. Please see the announcement on UNM Learn.

Today

- Gain-bandwidth product in different amplifier configurations
- High frequency model of a MOSFET
- High frequency response of a MOSFET based amplifier
- Intrinsic frequency response of BJTs and MOSFETs

Gain-bandwidth product (GB or GBW)



$$f_{BW} = f_H - f_L \cong f_H \qquad GB = |A_v|_{max} \cdot f_H$$

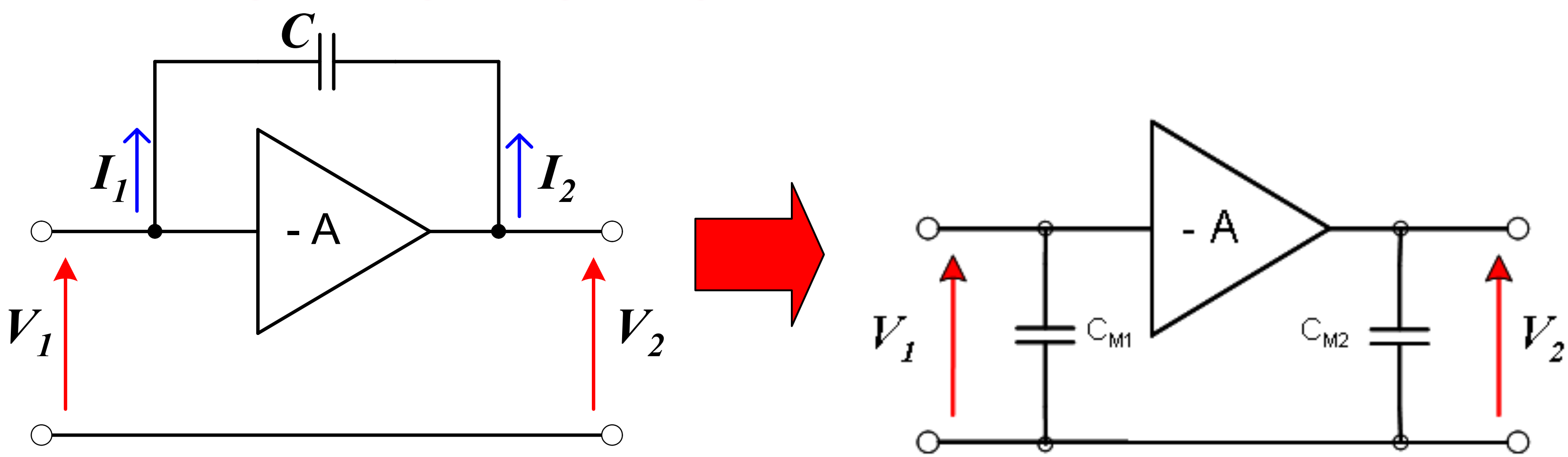
GBW is a figure of merit of amplifiers

A high GBW is desirable

GBW and Miller effect

The Miller effect associated to the capacitors between the input and the output limits performance of amplifiers in CE configuration.

$$f_{BW} = f_H - f_L \cong f_H \qquad GB = |A_v|_{\max} \cdot f_H$$



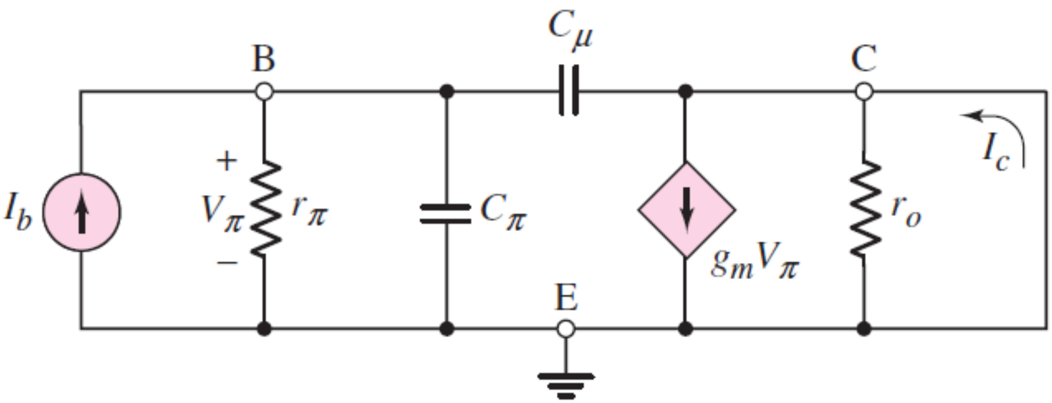
Any increase of the GBW is hindered by the Miller effect

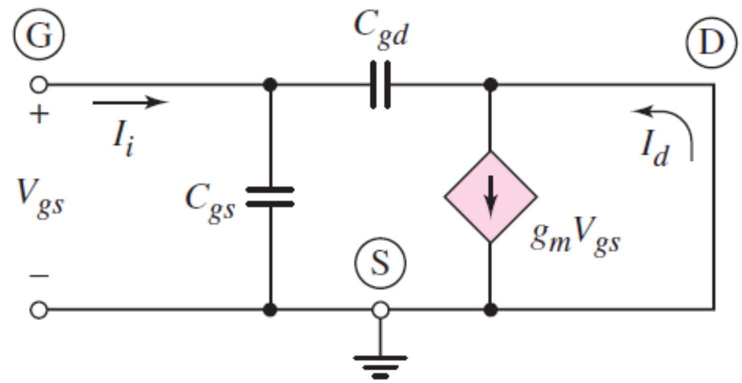
$$C_{M1} = C(1 + |A_v|_{max}) \quad C_{M2} = C\left(1 + \frac{1}{|A_v|_{max}}\right)$$

$$C_{M1} \gg C_{M2} \rightarrow f_H$$

$A \uparrow \Rightarrow C_{M1} \uparrow \Rightarrow f_H \downarrow \Rightarrow$ GBW constant

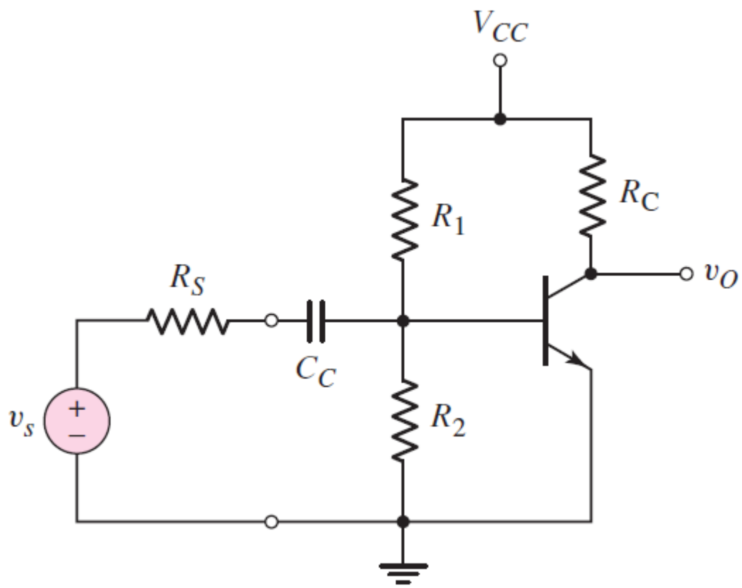
Strategies to increase the GBW

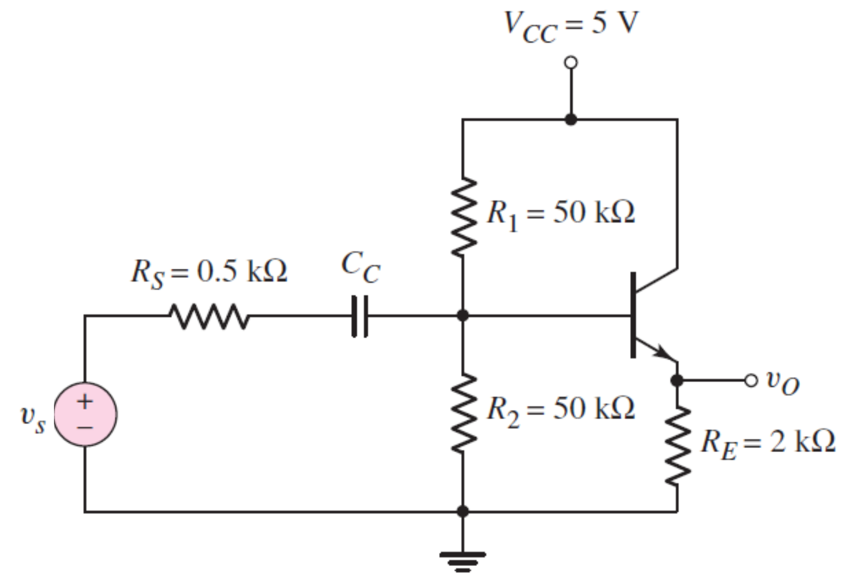


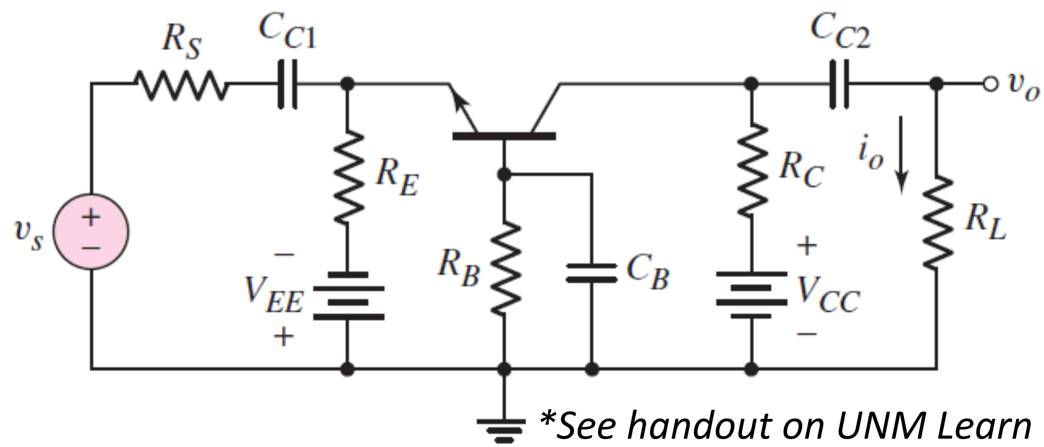


- Reduce the capacitance between input and output which can be achieved by reducing the area of the B-C junction.
- Use a different amplifier configuration.

Miller effect in CE, CB, and CC amplifiers

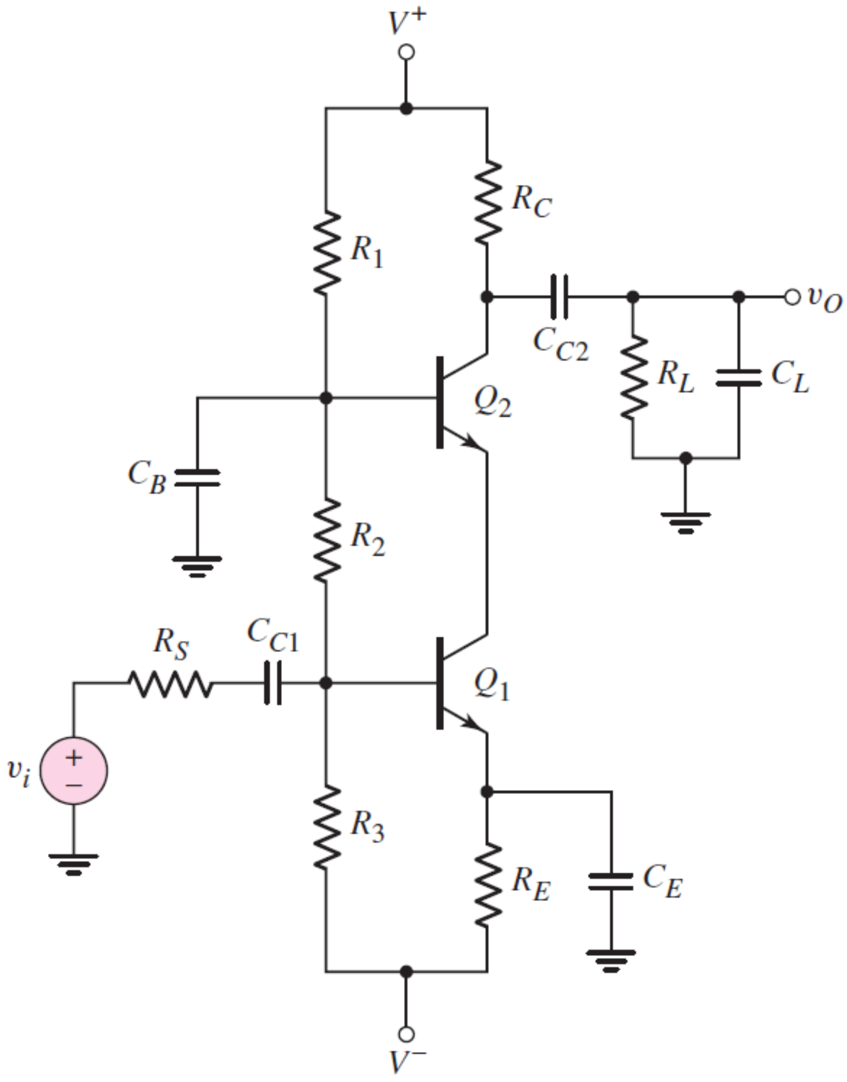






**See handout on UNM Learn (Lecture 19 folder)*

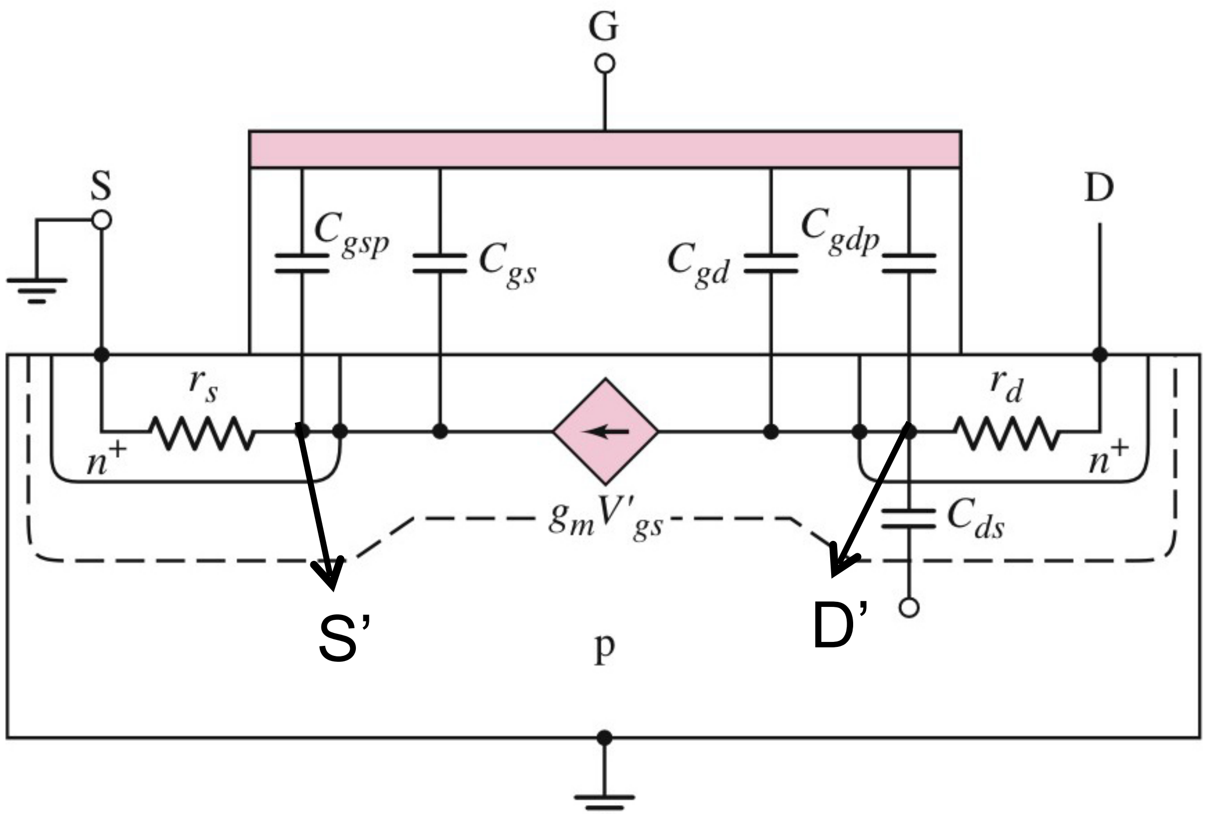
Cascode circuit



- High input impedance
- High gain
- High bandwidth

*See the two handouts about the cascode on UNM learn *(Lecture 19 folder)*

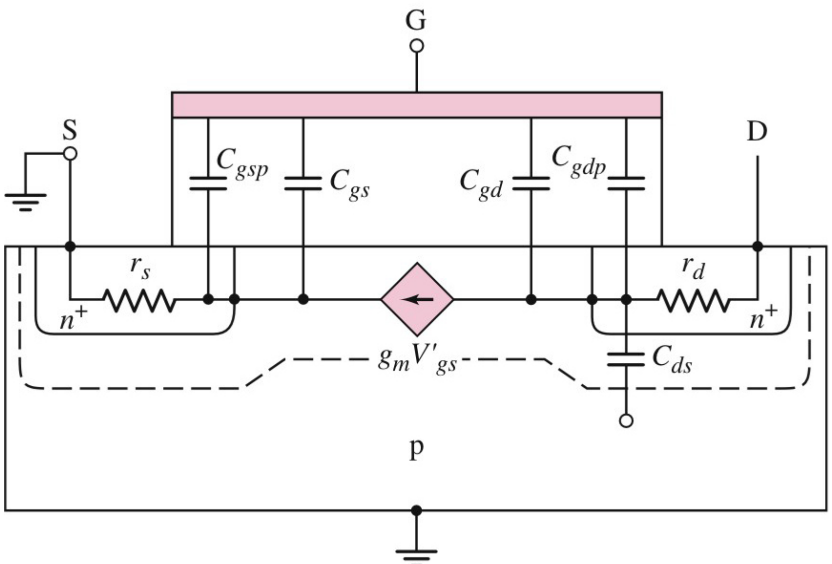
Inherent Resistances and Capacitances in an NMOS



Two types of capacitive effects are inherent to a MOSFET:

- the gate capacitive effect
- the junction capacitive effect at the source-body and at the drain-body terminals

The gate capacitive effect



The gate electrode forms a parallel-plate capacitor with the channel, the source and the drain, with the oxide layer serving as the capacitor dielectric.

The gate capacitive effect is modeled by four capacitances:
C_{gs}, C_{gd}, C_{gsp}, C_{gdp}.

C_{gs}, C_{gd} describe variation of charges in the channel region in response to the applied V_g.

$$C_{gs} = C_{gd} = \frac{1}{2} WL\, C_{ox} \quad \text{(triode region)}$$

Capacitance between the gate electrode and a channel with uniform width from S to D

$$\left.\begin{aligned} C_{gs} &= \frac{2}{3} WL\, C_{ox} \\ C_{gd} &= 0 \end{aligned}\right\} \quad \text{(saturation region)}$$

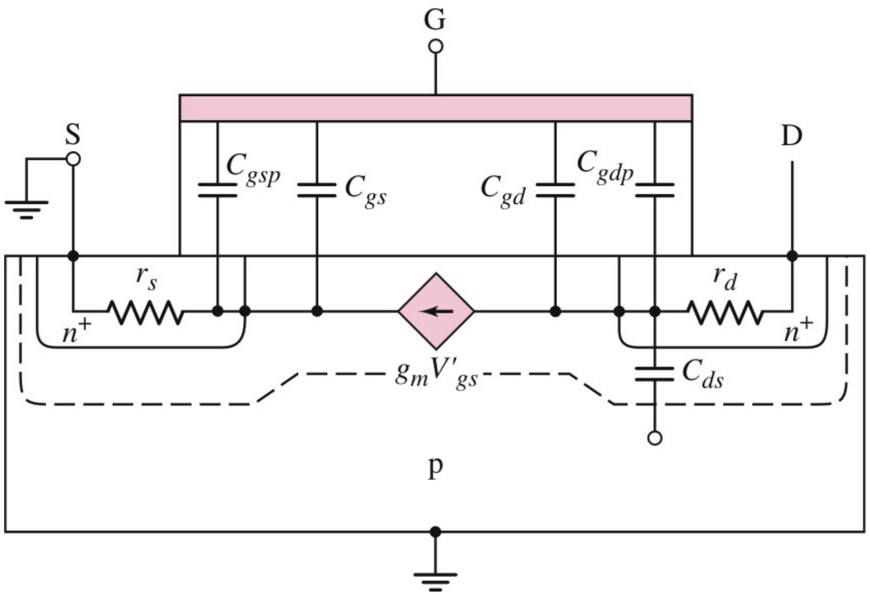
Capacitance between the gate electrode and a channel with non-uniform width from S to D

C_{gsp}, C_{gdp} or C_{ov}: parasitic capacitances due to fabrication issues.

$$C_{ov} = WL_{ov}\, C_{ox} \qquad L_{ov} = 0.05 \text{ to } 0.1\, L$$

Capacitance between the gate electrode and the source and drain S to D

The junction capacitive effect



*The **junction capacitive effect*** is associated with the reverse biased junctions between the source (S) and the body (B) and the drain (D) and the body.

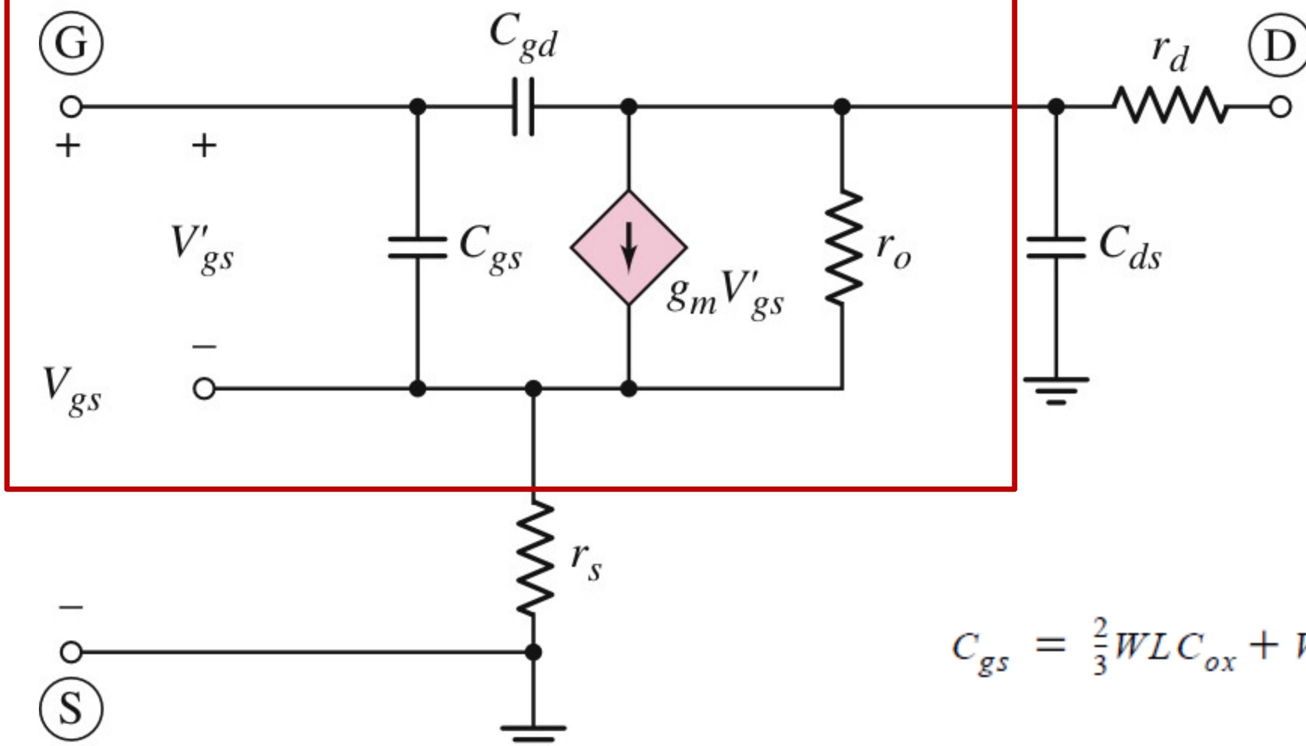
The junction capacitive effect can be modeled by the two capacitances: $\boldsymbol{C_{sb}}$ and $\mathbf{C_{db}}$.

C_{sb}, C_{db} describe variation of fixed charge density at the S-B and D-B junctions in response to the applied v_g.

Often S and B are at the same potential. In that scenario the impedance associated with C_{sb} is zero and C_{db} is also indicated as C_{ds}.

Equivalent Circuit for an Common Source NMOS

Simplified model

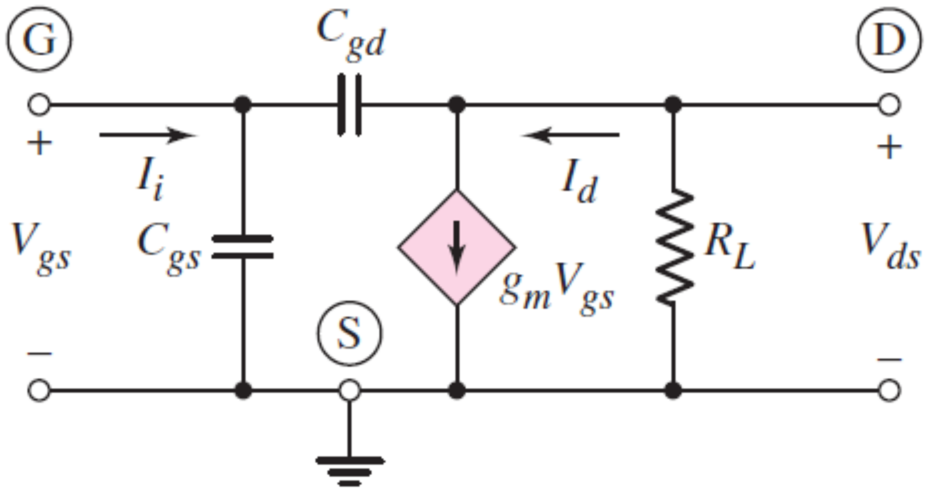


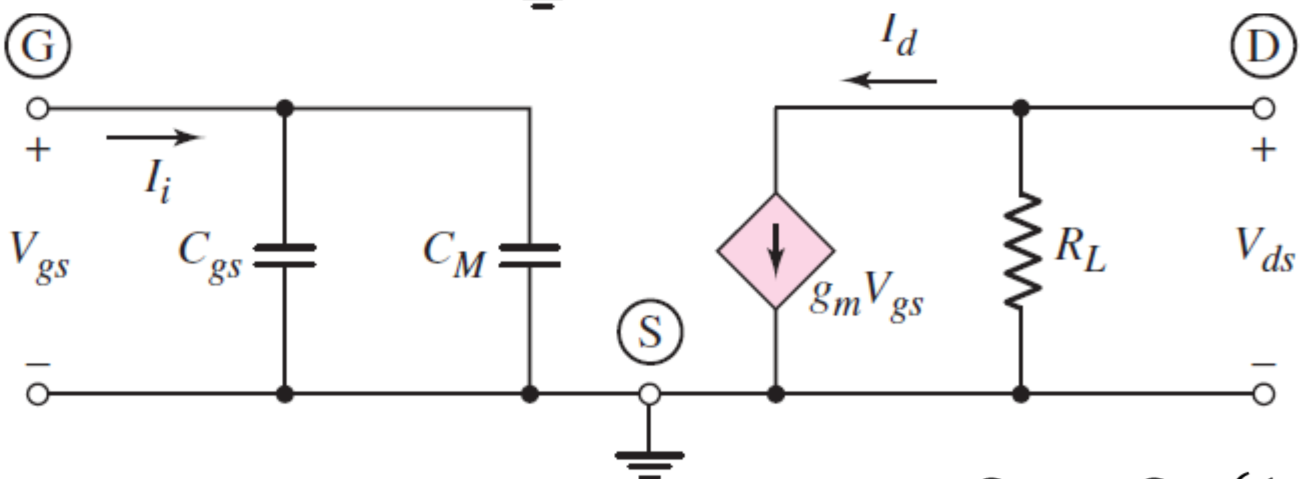
$$C_{gs} = \frac{2}{3} W L C_{ox} + W L_{ov} C_{ox}$$

$$C_{gd} = W L_{ov} C_{ox}$$

Note that C_{gs} *and* C_{gd} *include* C_{gsp} *and* C_{gdp}*.*

Miller effect



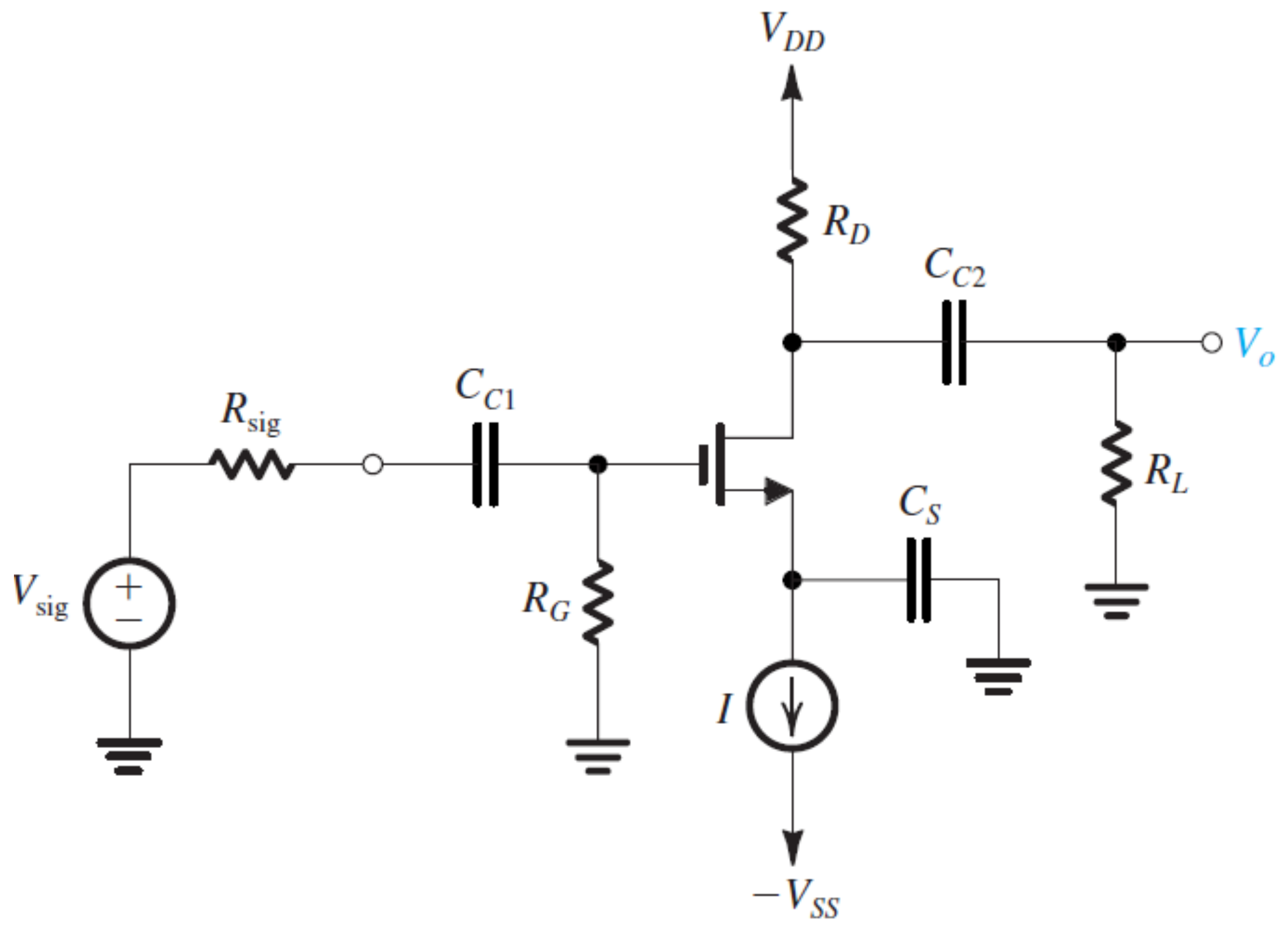


$$C_M = C_{gd}(1 + A)$$

Note that the Miller capacitance at the output can be neglected as it is very small.

Lecture 19-In class problem

Determine expressions for all the upper corner frequencies of the circuit below

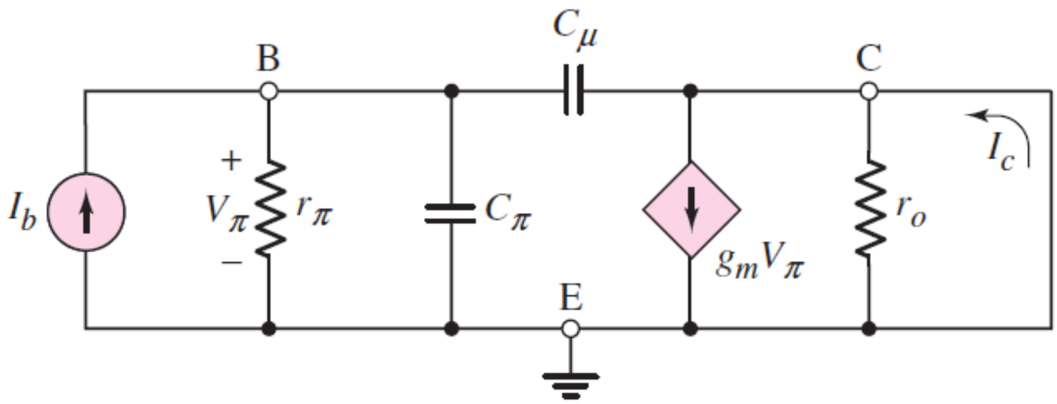


Intrinsic frequency response of a BJT

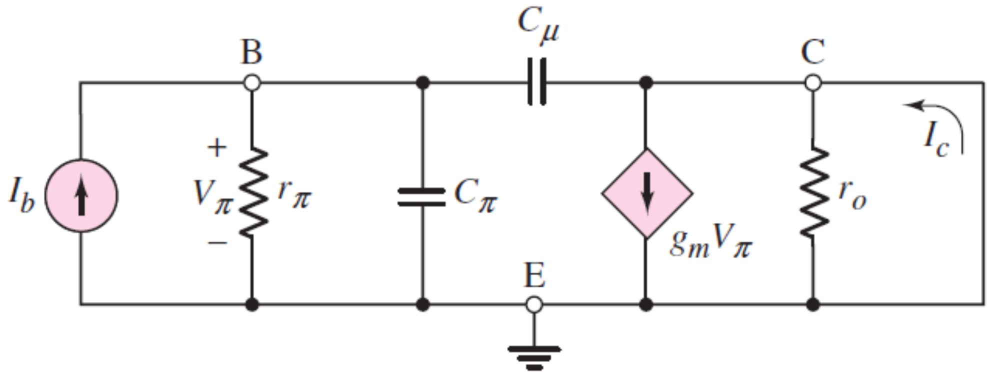
How does one assess the intrinsic frequency response of a BJT?

By evaluating

- its short circuit current gain vs frequency
- its cut-off frequency or unity current gain frequency.



Intrinsic frequency response of a BJT



$$A_i = \frac{I_c}{I_b}$$

KCL at B

$$I_b = \frac{V_\pi}{r_\pi} + \frac{V_\pi}{\frac{1}{j\omega C_\pi}} + \frac{V_\pi}{\frac{1}{j\omega C_\mu}} = V_\pi\left[\frac{1}{r_\pi} + j\omega(C_\pi + C_\mu)\right] \quad (1)$$

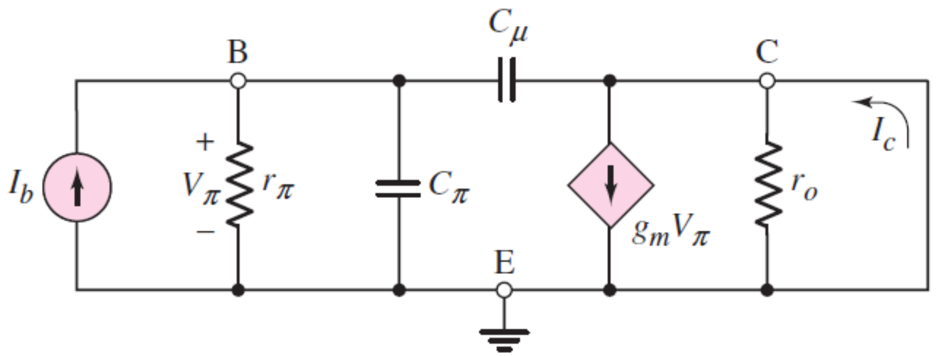
KCL at C

$$\frac{V_\pi}{\frac{1}{j\omega C_\mu}} + I_c = g_m V_\pi \qquad I_c = V_\pi(g_m - j\omega C_\mu) \qquad V_\pi = \frac{I_c}{(g_m - j\omega C_\mu)} \quad (2)$$

Plugging the expression obtained for V_π in eq. (1) yields

$$I_b = I_c \cdot \frac{\left[\frac{1}{r_\pi} + j\omega(C_\pi + C_\mu)\right]}{(g_m - j\omega C_\mu)}$$

Intrinsic frequency response of a BJT



$$A_i = \frac{I_c}{I_b}$$

$$A_i = \frac{I_c}{I_b} = h_{fe} = \frac{(g_m - j\omega C_\mu)}{\left[\frac{1}{r_\pi} + j\omega(C_\pi + C_\mu)\right]}$$

Hence the short circuit current gain for a BJT is

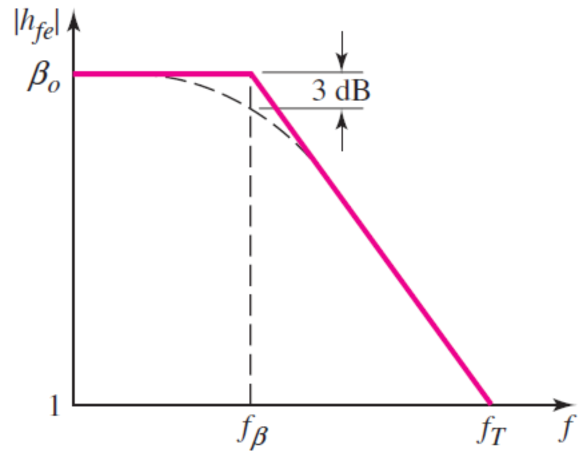
If we assume typical circuit parameter values of C_μ=0.05 pF, g_m=50 mA/V, and a maximum frequency of f=500 MHz, then we see that $\omega C_\mu << g_m$. Therefore,

$$h_{fe} \cong \frac{g_m}{\left[\frac{1}{r_\pi} + j\omega(C_\pi + C_\mu)\right]} = \frac{g_m r_\pi}{1 + j\omega r_\pi (C_\pi + C_\mu)}$$

or $$h_{fe} = \frac{\beta_o}{1 + j\left(\frac{f}{f_\beta}\right)} \qquad f_\beta = \frac{1}{2\pi r_\pi (C_\pi + C_\mu)}$$

Intrinsic frequency response of a BJT

The internal capacitances of the BJT leads to a low pass response



The cut-off frequency of the transistor is the frequency which yields a unity short-circuit current gain.

$$|h_{fe}| = \frac{\beta_o}{\sqrt{1+\left(\frac{f}{f_\beta}\right)^2}} \qquad |h_{fe}| = 1 = \frac{\beta_o}{\sqrt{1+\left(\frac{f_T}{f_\beta}\right)^2}} \qquad 1 \cong \frac{\beta_o}{\sqrt{\left(\frac{f_T}{f_\beta}\right)^2}} = \frac{\beta_o f_\beta}{f_T}$$

$$f_T = \beta_o f_\beta \quad f_\beta = \frac{1}{2\pi r_\pi (C_\pi + C_\mu)} \qquad f_T = \beta_o \left[\frac{1}{2\pi r_\pi (C_\pi + C_\mu)}\right] = \frac{g_m}{2\pi (C_\pi + C_\mu)}$$

Intrinsic frequency response of a BJT

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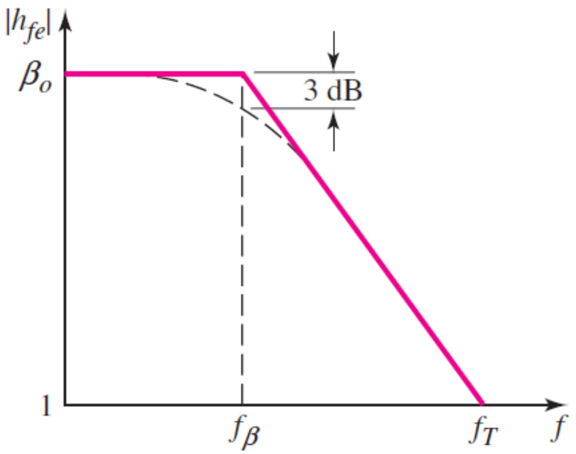

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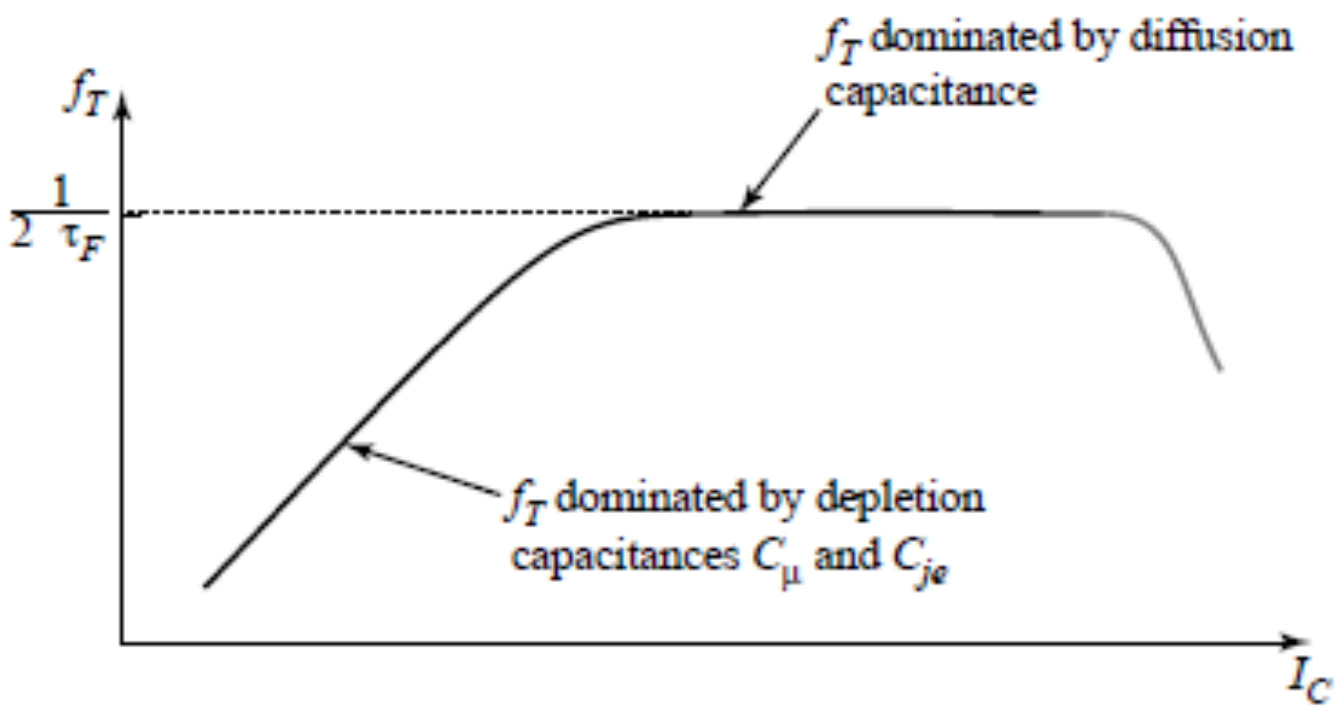
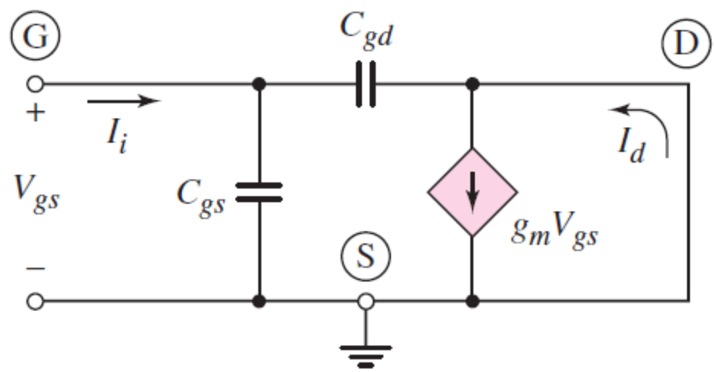
$$f_T = \beta_o f_\beta \quad f_\beta = \frac{1}{2\pi r_\pi (C_\pi + C_\mu)} \qquad f_T = \beta_o\left[\frac{1}{2\pi r_\pi (C_\pi + C_\mu)}\right] = \frac{g_m}{2\pi (C_\pi + C_\mu)}$$

Intrinsic frequency response of a BJT



$$C_\pi = C_{je} + g_m \tau_F \quad \omega_T = \frac{I_C / V_{th}}{(I_C / V_{th})\tau_F + C_{je} + C_\mu}$$

Intrinsic frequency response of NMOS



$$A_i = \frac{I_d}{I_i}$$

KCL at G

$$I_i = \frac{V_{gs}}{\dfrac{1}{j\omega C_{gs}}} + \frac{V_{gs}}{\dfrac{1}{j\omega C_{gd}}} = V_{gs}[j\omega(C_{gs} + C_{gd})] \quad (1)$$

KCL at D

$$\frac{V_{gs}}{\dfrac{1}{j\omega C_{gd}}} + I_d = g_m V_{gs} \qquad I_d = V_{gs}(g_m - j\omega C_{gd}) \qquad V_{gs} = \frac{I_d}{(g_m - j\omega C_{gd})} \quad (2)$$

Plugging the expression obtained for V_{gs} in eq. (1) yields

$$I_i = I_d \cdot \frac{[j\omega(C_{gs} + C_{gd})]}{(g_m - j\omega C_{gd})}$$

Intrinsic frequency response of NMOS

$$A_i = \frac{I_d}{I_i} = \frac{g_m - j\omega C_{gd}}{j\omega(C_{gs} + C_{gd})}$$

If we assume typical circuit parameter values of C_{gd}=10 fF, g_m=1 mA/V, and a maximum frequency of f=1 GHz, then we see that $\omega C_{gd} << g_m$. There fore,

$$A_i = \frac{I_d}{I_i} \cong \frac{g_m}{j\omega(C_{gs} + C_{gd})}$$

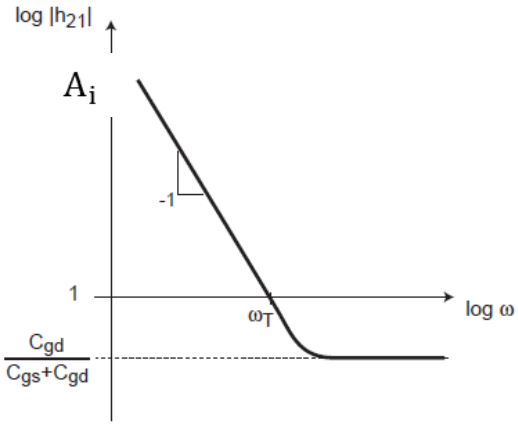
The internal capacitances of the NMOS lead to a low-pass response

or

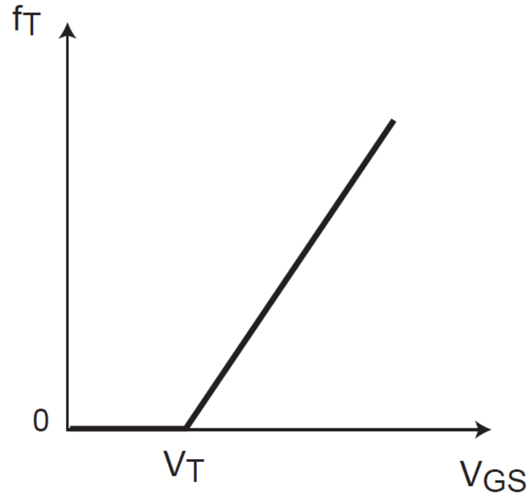
$$f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd})}$$

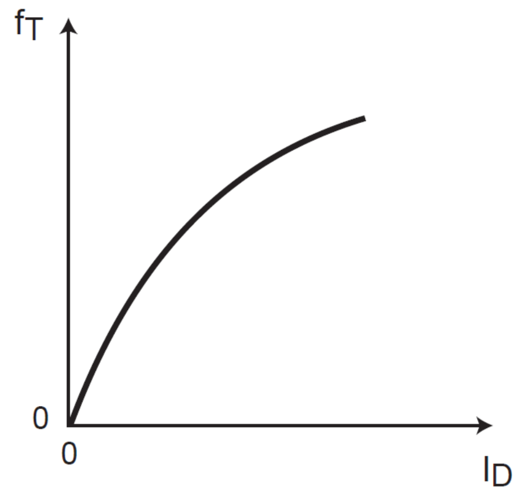
At very high frequencies $\omega C_{gd} >> g_m$ and

$$A_i = \frac{C_{gd}}{C_{gs} + C_{gd}}$$



Intrinsic frequency response of NMOS





f_T depends on

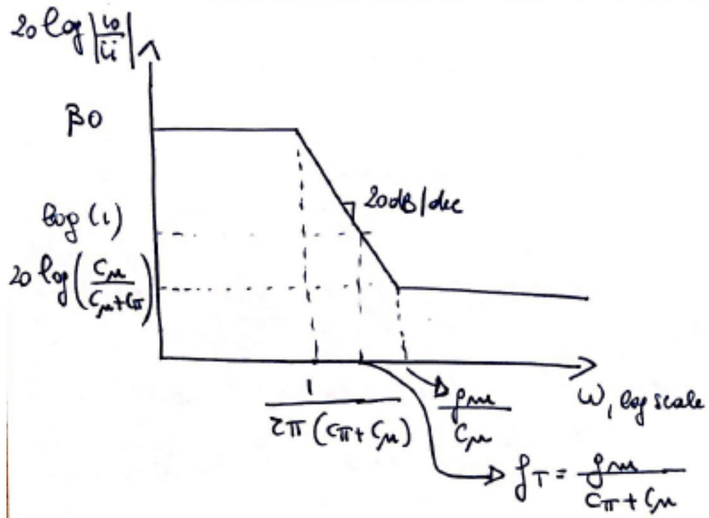
- transistor biasing
- mobility
- channel length
- Overlap length between the gate with the source and drain

$$f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd})}$$

$$\frac{1}{2\pi f_T} \simeq \frac{C_{gs}}{g_m} = \frac{\frac{2}{3}LWC_{ox}}{\frac{W}{L}\mu C_{ox}(V_{GS} - V_T)} = \frac{L}{\mu \frac{3}{2}\frac{V_{GS}-V_T}{L}}$$

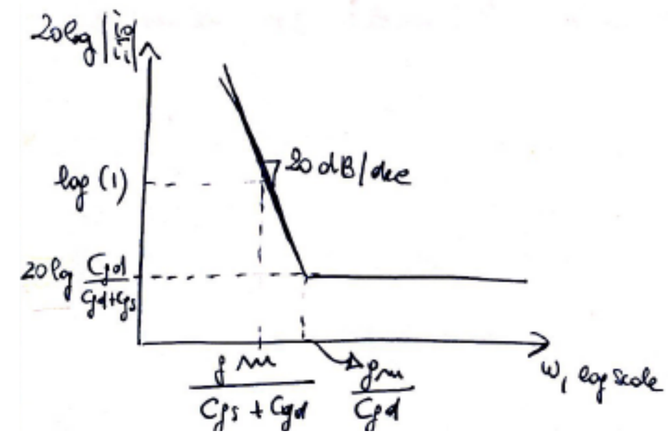
BJT vs MOSFET

BJT



$$f_T = \frac{g_m}{2\pi(C_\pi + C_\mu)}$$

MOSFET



$$f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd})}$$

- BJTs have larger parasitic capacitances than FETs (~pF vs fF).
- BJTs have much larger transconductance than FETs.
- Therefore, the gain-bandwidth product of bipolar amplifiers is usually larger than that of comparable FET amplifiers.

**See the three handouts that I previously posted on BJT vs. MOSFETS on UNM Learn (Handout folder)*